

STRAIN RATE EFFECT ON THE MECHANICAL BEHAVIOUR OF A TEXTILE REINFORCED CEMENT COMPOSITE

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ABSTRACT: The static tensile behaviour of Textile Reinforced Cement Composites is known and can be modeled adequately. However, using these static material properties under dynamic loadings such as impact and seismic loadings, can cause over- or underestimation of the material due to effects of strain rate. This work focuses on the strain rate dependency of a specific textile reinforced cement composite under tensile loadings at strain rates equivalent to quasi static applications towards low velocity impacts. It was found that the main damage mechanisms of this material stay the same. However cracking of the cement matrix is delayed to higher stress levels.

1 INTRODUCTION

In civil engineering applications, more and more composite materials are being used nowadays. This trend is not only visible in aviation and automobile industries. Also in the design of building constructions many attempts are undertaken to replace or to partially replace traditional building materials (as concrete and steel) by advanced composite materials. Some good examples can be found in many skyscrapers, where mostly weight is of major importance. A lot of these constructions are subjected to impact or seismic loadings during their lifetime, which makes it necessary to implement dynamic behaviour into their design. Implementation of dynamic loadings into the design of a structure using the static material behaviour can lead to an underestimation of the materials' performance and thus an overweighed design. On the other hand it can lead to unexpected failure of the material due to an overestimation of its dynamic properties. Therefore it is necessary to quantify the behaviour of the material under dynamic loading conditions which imply different strain rates. Many composite materials behave differently at different strain rates and several researchers have obtained results for the evolution of strength and stiffness of a specific composite material as a function of strain rate. These results not always correspond to each other due to the lack of standardized tests to obtain material properties at higher strain rates and to difficulties encountered during the tests.

A promising group of materials which can (partially) replace traditional materials in building constructions are High Performance Fibre Reinforced Cement Composites (HPFRCC). These materials distinguish themselves from traditional fibre reinforced concrete by their much higher mechanical performance (see Fig. 3.1. in section 3). Next to a strain hardening behaviour under tensile loading, providing strength, a HPFRCC is characterized by a high

energy absorption capacity. A special group in this large group of HPFRCC, which have had some applications in buildings [Heg06], are textile reinforced concrete composites. Due to the use of textile reinforcements instead of loose fibres the fibre volume fractions increase significantly. These materials therefore show a very clear strain hardening behaviour leading to high strength. Moreover, they show high energy absorption due to different damage mechanisms implying non linear behaviour. This high energy absorption capacity could be used either to implement accidental loading, such as impact and earthquakes, into the design of building structures, or to design special sacrificial building components with these materials to protect civil buildings. In the present paper, the effect of strain rate on the mechanical tensile behaviour of a specific glass textile reinforced cement composite is investigated. The aim is to obtain insight in the material behaviour at strain rates corresponding to those present during low velocity impact events (mass impact).

2 STRAIN RATE EFFECTS ON COMPOSITES

When it comes to impact problems and dynamic behaviour, it is very useful to develop a sense of the range of strain rates which one can expect in such problems. A good overview of different strain rates depending on the performed tests is given in Fig. 2.1 [Fie04, Fer05]. Most servo- hydraulic machines can obtain strain rates up to 10^0 s^{-1} , which can be compared to rather quick static loadings. Specialized low velocity impact machines, such as a drop weight test or a pendulum test, can provide strain rates up to 10^2 s^{-1} . Higher strain rates are typically obtained by using a split Hopkinson/Kolsky bar test. These rates simulate rather fast impact events as a bullet impact. In this paper, results will be presented of tests within the static range going towards dynamic events.

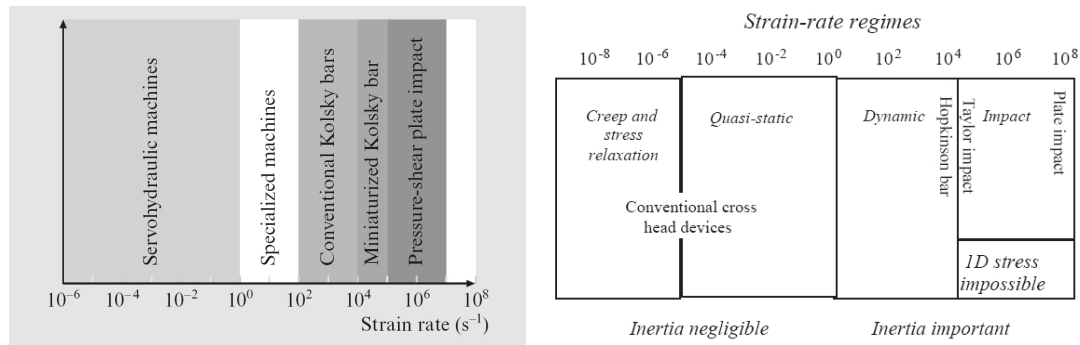


Fig. 2.1. Typical strain rate domains linked with testing machines. [Fie04, Fer05].

Many composite materials were found to be strain rate sensitive [Bar96, Fer05, Sch08, Kim08, Can09]. The investigations available in most of these publications deal with the strain rate sensitivity of polymer matrix composites with glass fibre or carbon fibre reinforcements. In the middle nineties Barré et al. [Bar96] discussed a large amount of literature on the strain rate dependency of polymer composite materials. In this review a wide range of strain rates was covered (from $2 \times 10^{-4} \text{ s}^{-1}$ to $2 \times 10^3 \text{ s}^{-1}$) and in most of these efforts influences of strain rate on the strength and stiffness were found. However, depending on the authors there seemed to be some controversy in the results. This indicated that the results strongly depend on the components of the composite material and that there is no standard testing procedure. In more recent work of Fereshteh-Saniee, Majzoobi and Bahrami [Fer05] tensile tests are performed on glass-epoxy composites at strain rates ranging from 0.0001 to 0.11 s^{-1} . They concluded that even at these rather low strain rates, the material was strain rate sensitive. The

differences were mainly situated in the strength and in a minor way the strain rate had an effect on the stiffness. These researchers were able to determine an analytical model to predict the strength at different strain rates. Schoßig et al. [Sch08] did some experimental work on glass fibre reinforced Polypropylene and Polybutene-1 composites. Using a high speed tensile test, they were able to test specimens in a range of 0.007 up to 174 s^{-1} . In this study the effect of strain rate was also present in the tensile stress-strain curves. It was found that strain rates above 20 s^{-1} cause a spectacular increase in mechanical properties, while the effect at lower strain rates is present but less distinctly.

One of the most interesting publications on this topic related to TRC-materials was probably written by Kim, El-Tawil and Naaman [Kim08]. HPFRCC specimens were tested in tension in this publication and this at different strain rates ranging from 0.0001 to 0.1 s^{-1} . The investigated HPFRCC are steel fibre reinforced cement matrices. The fibres were mixed into the matrix in an amount of 1 or 2 vol.-%, which is rather low compared to textile reinforced cement composites. In these tests it was found that in some cases there is a strain rate effect on the cracking of the matrix and the strength. Cadoni, Meda and Plizzari [Cad09] performed tests on a similar FRC material, but at higher strain rates. They used a split Hopkinson bar test to investigate the strain rate dependency of this material at strain rates of 50 s^{-1} , 100 s^{-1} and 200 s^{-1} . This study indicated that for an FRC material with steel and PVA fibre reinforcement the ratio between dynamic and static strength (also called Dynamic Increase Factor or DIF) increases with strain rate. However these materials become more brittle at higher strain rates.

3 STUDIED MATERIAL AND STATIC BEHAVIOUR

3.1 Material

The textile reinforced cement composite investigated in this research is a glass textile reinforced Inorganic Phosphate Cement (IPC) [IPC] with non woven fabrics (Owens Corning M705 with a surface weight of 300 g/m^2) as reinforcement. IPC, commercially available under the name Vubonite®, was developed at the Vrije Universiteit Brussel and consists of a liquid component based on a phosphoric acid solution containing inorganic metal oxides and a calcium silicate powder component. Compared to conventional TRCs, this material has the advantages of possessing a neutral pH after curing and being absolutely fire resistant. The neutral pH-value is a major advantage when it comes to compatibility with glass fibres. In a normal Portland cement, glass fibres are chemically attacked by the alkaline environment of the cement, which is not the case in an IPC matrix. Fire resistance could on the other hand be very interesting in explosion applications.

3.2 Static behaviour

The investigated textile reinforced IPC shows linear elastic behaviour up to failure when it is loaded in the direction of the non woven fabrics in compression (in plane) [Cuy01]. However, compared to most other composite materials, a TRC behaves strongly non-linear under tensile loading. This non-linearity is due to the cement matrix which has a rather low failure stress due to its low strain capacity. Since the fibre-matrix bond is rather weak compared to the bond in traditional composite materials, the fibres will be able to bridge the cracks due to debonding of the fibres from the matrix. If sufficient fibres are present, the stresses within a cross section, wherein a crack is situated, can be carried by the fibres.

A typical stress-strain curve obtained from a tensile test on a TRC with 2D random chopped strand glass fibre mats impregnated by an IPC matrix is presented in Fig. 3.1. Generally, three distinct stages can be identified: a first linear elastic stage where the fibre-matrix bond is globally adhesive. Once the global composite stress exceeds the matrix strength (around 10 MPa), multiple cracking will occur leading to a fine parallel crack pattern and a deflection of the stress-strain curve. In the vicinity of a crack, the fibre-matrix bond is assumed to be reduced to a frictional shear stress. When all cracks are formed, the material behaves linear again (with a lower slope) and only the fibres will carry extra load up to failure of the composite.

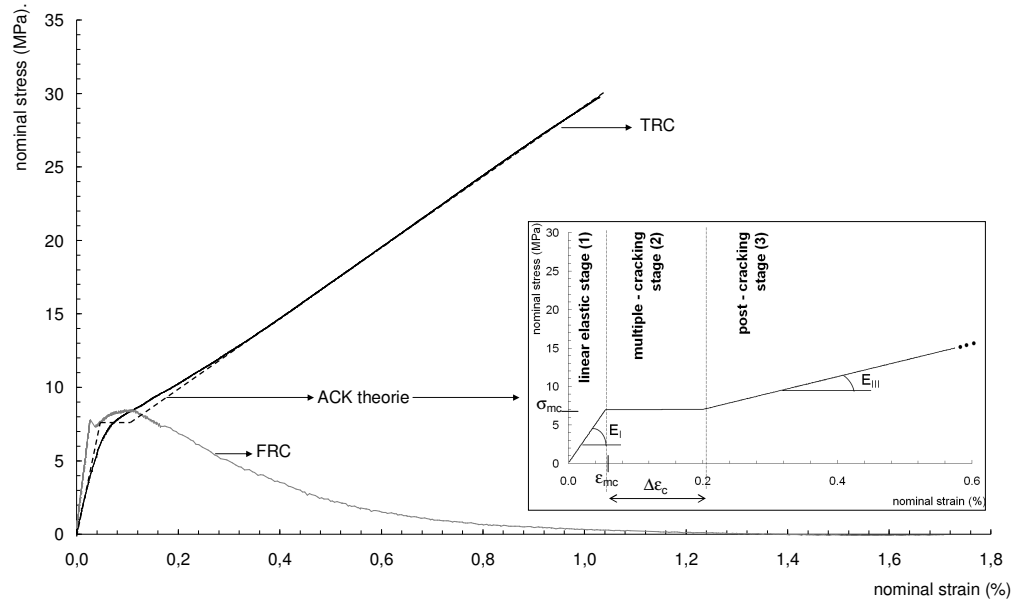


Fig. 3.1. Typical stress-strain curves of traditional FRC and a TRC laminate with visualization of the ACK-theory.

In order to determine the influence of strain rate on the tensile behaviour of TRCs, it is essential to define a parameterised model, which can represent each individual curve. In literature, a few models are available [Ave71, Cur98, Cuy06, Heg06]. One of these models, developed by Aveston, Cooper and Kelly, is called the ACK-theory [Ave71]. This is a model representing the three different stages mentioned above with three linear pieces (Fig. 3.1). This model is limited by some assumptions, such as the assumption of uni-directional fibre reinforcement. In a later stage this theory was adapted for more advanced cement composites. The main parameters of this model are:

- the elastic modulus of the first linear elastic stage (E_I).
- the multiple cracking stress (σ_{mc}) and strain (ϵ_{mc}) to determine the point where the second stage begins.
- the total strain in the composite due to the multiple cracking process ($\Delta\epsilon_c$).
- the elastic modulus of the third stage (E_{III}).
- the tensile composite strength at the end of stage III (σ_{cu}).

This theory however shows some discrepancy with the real behaviour of the composite, where multiple cracking will appear in a certain stress range and not at a deterministic stress level. This theory was adapted by Cuypers et al. [Cuy06] using a 2 parameter Weibull distribution function to describe the multiple cracking stage.

In the experiments described in section 4, the second stage of the curve is rather small causing an abrupt transition from the first to the third stage. The model of Cuypers et al. is difficult to

fit since it is not certain to find the absolute minimum. Therefore, in this paper, a piecewise linear fit with two linear stages will be used to obtain an evolution of the material behaviour with increasing strain rate. For this model the following parameters are determined:

- the elastic modulus of the first linear elastic stage (E_I).
- the elastic modulus of the third stage (E_{III}).
- the tensile composite strength at the end of stage III (σ_{cu}).
- the x- and y- coordinates of the intersection point of the two straight lines. These parameters represent the multiple cracking of the matrix.
- the total energy obtained from the area under the stress-strain curve.

A remark can be formulated concerning the E_I parameter: the amount of data points in this stage is limited resulting in a large scatter when fixed boundaries for the calculation of the slope are used. Therefore a least square method with a variable amount of data points is used to determine the best fit. This gives better results, but it is still not completely reliable. The scatter on this parameter is even increased by previously induced damage.

4 EXPERIMENTAL STUDY

4.1 Specimen preparation and testing scheme

The specimens are made of an IPC matrix reinforced with 2D random glass fibre mats. The laminated plates are produced by hand lay-up. A layer of matrix material is spread out on a flat surface which is coated with a demolding agent. Then a layer of fibres is applied and impregnated with a roller. This is repeated until the aimed amount of layers is obtained and afterwards the laminate is sealed with a plastic foil to prevent early evaporation of water. After one day of curing at room temperature, the plates are post cured at 60 °C for another 24 h. Subsequently specimens with dimensions 250 mm x 25 mm were cut out with a water fed diamond saw. The thickness of the specimens depends on the amount of fibre layers that is applied. Each plate provides 20 specimens which are divided into 5 groups of 4 specimens. These five groups were tested at different strain rates from $1 \cdot 10^{-4} \text{ s}^{-1}$ to 0.05 s^{-1} . The different strain rates are obtained by variation of the loading speed during tensile tests. The cross head speed is varied respectively from 1 mm/min to 500 mm/min (an overview is given in table 4.1). All of these tests were performed on a universal testing machine (Instron 4505) with a 10 kN load cell and an extensometer with a basis of 50 mm. Six different plates with different properties were manufactured. An overview of the manufactured plates and their properties is given in table 4.2. The aligned fibre volume fraction given in this table is calculated by dividing the fibre volume fraction (V_f) by 3 [Ben90].

Table 4.1. strain rates at different loading speeds.

Loading speed (mm/min)	Strain rate (s^{-1})	Test duration (s)
1	0,0001	240
10	0,001	24
100	0,01	2,4
200 ¹	0,02	1,2
250 ¹	0,025	0,96
500	0,05	0,48

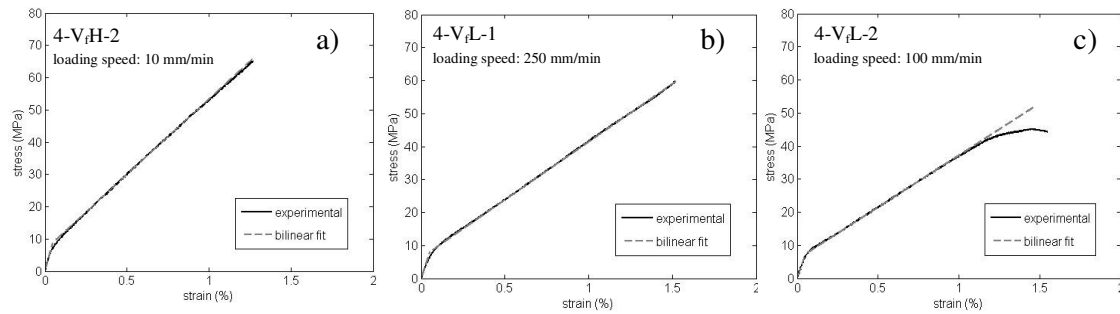
¹ for the series 4-V_fH-1 and -2 the speed was 200 mm/min instead of 250 mm/min

Table 4.2. properties of the produced laminates

Name	Number of layers	Thickness (mm)	Standard deviation (mm)	Average V_f (%)	Average V_f aligned (%)
4- V_f H-1	4	2,22	0,05	21,3	7,1
4- V_f H-2	4	1,98	0,14	23,8	7,9
4- V_f L-1	4	2,49	0,05	19,1	6,4
4- V_f L-2	4	2,44	0,05	19,4	6,5
8- V_f H-1	8	4,46	0,11	21,2	7,1
8- V_f H-2	8	4,01	0,20	23,5	7,8

4.2 Results

First a closer look is given to the fitting of the stress-strain curves. As described above, the real stress-strain curve is fitted by a piecewise linear curve and consequently does not necessarily return good approximations. In Fig. 4.1 some fitted curves are presented. It is clear that the fit is very good except in plot c). Here the fit clearly deviates from the experimental curve. This is due to pull-out of the fibres which is not included in the model. Consequently, the stresses at a strain near the failure strain will be overestimated by the model. Therefore the maximum strain and the strength of the composite will be taken from the experimental data. Fibre pull-out did only occur in a few cases, while fibre fracture was mainly the damage mechanism leading to failure. The maximum deviation on the calculated energy absorption (area under the curves) between the real curves and the piecewise linear fit stays below 5 %.

**Fig. 4.1.** Fitting of piecewise linear model on experimental stress-strain curves

From Table 4.2 it was clear that two plates with the same theoretical properties, such as 4- V_f H-1 and 4- V_f H-2, do not show the same fibre volume fractions due to the differences in the thickness and the scatter on this parameter. Therefore, all results were kept separately for each individual plate. In this paper only the results of one series will be shown. The other series mainly exhibit the same trends in the results with some minor deviations.

The evolution of the above described parameters for laminate 4- V_f L-2, as a function of the loading speed, is presented in Fig. 4.2 in separate graphs. In these graphs each point represents the mean value of at least three and maximum four experimentally determined values. The error bars that are drawn correspond to one standard deviation on each side of the data point. The scatter on these results is rather high, for instance in graph a) and b) representing the strain rate effect on respectively the strength and the maximum strain of the composite material. Nevertheless, the mean values of these two parameters hardly change with increasing loading speed. There seems to be no influence of the strain rate on the

strength and maximum strain of the composite as well as on the modulus of the first and the third stage (graph c) and d)).

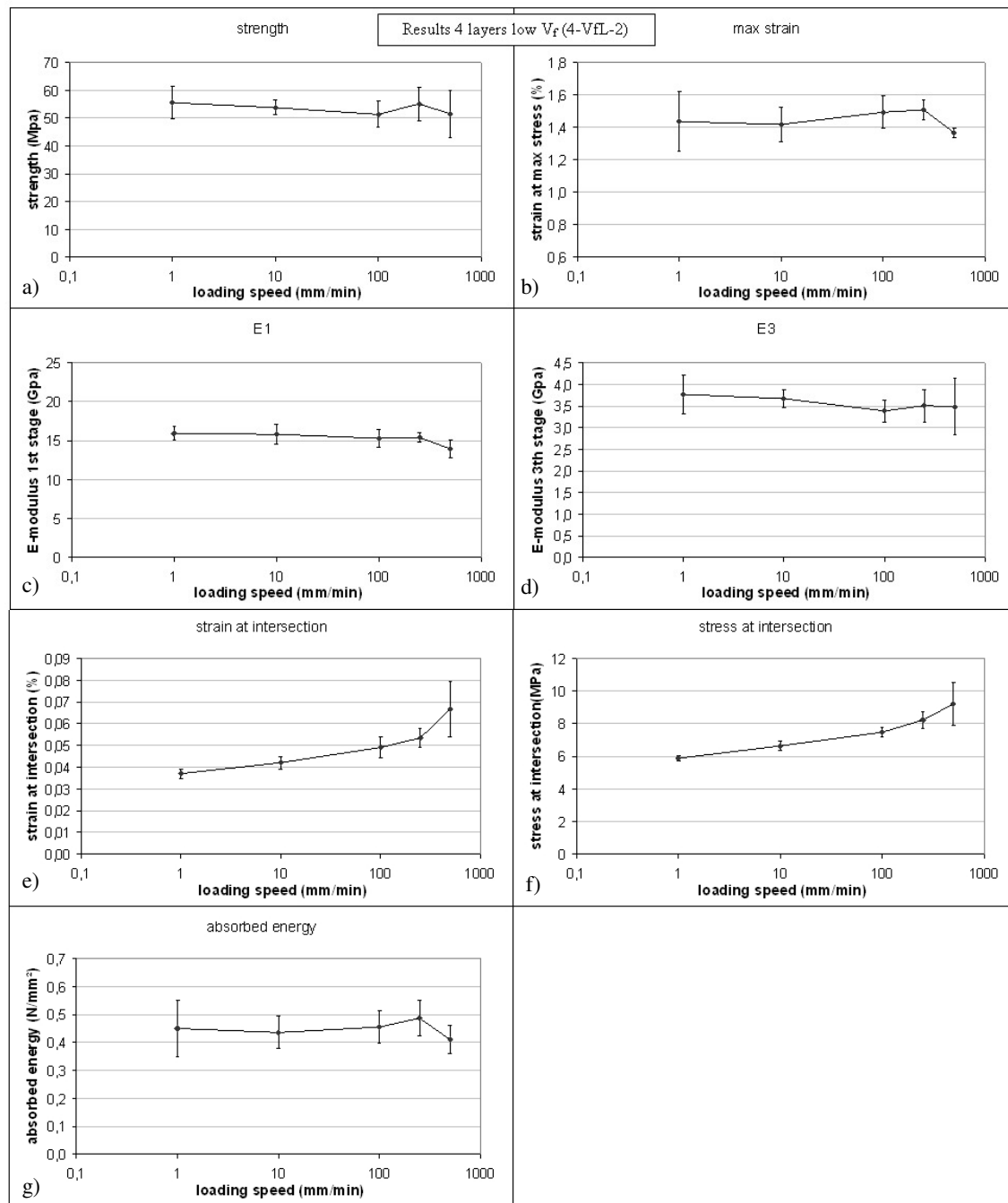


Fig. 4.2. Results of the strain rate effect on laminate 4-V_fL-2.

In contrast with the discussed parameters, strain rate clearly has an effect on the stress and strain at the intersection point, as depicted in graphs e) and f). These parameters increase with increasing strain rate and it seems that they will even augment more at higher strain rates. The effect of the latter parameters on the total absorbed energy is rather small, since they represent only the first stage of the stress-strain curve. The data points in graph g) consequently follow mainly the trends of strength and maximum strain.

The most acceptable explanation for the delay of the multiple cracking process to higher stress levels is that at higher testing speeds, flaws (very small defects) in the cement matrix don't have the time to grow due to the fast loading. The higher strain rate might also influence the bond between fibre and matrix.

Similar tests at identical loading speeds were performed on the five other plates. These tests confirmed the increase of the values of the intersection point with increasing strain rate. In some cases a slight increase in either strength or maximum strain was noticed. Whether there is an influence of the strain rate on these values is not clear due to the contradictory results. It was however found that the changes in these parameters were only due to differences in fibre volume fraction between several data series of the same graph. A more objective value representing the strength of the composite without influence of fibre volume fraction is the fibre strength at the moment of failure which can be calculated with the following formula:

$$\sigma_{f,\max} = \frac{\sigma_c}{V_{f,\text{aligned}}} \quad (4.1)$$

where: $\sigma_{f,\max}$ = the maximum fibre stress (MPa);
 σ_c = the composite strength (MPa);
 $V_{f,\text{aligned}}$ = the amount of fibres in the direction of the loading (%)

A plot including all data of all tested laminates is depicted in Fig. 4.3, showing that there is no effect of the strain rate on the fibre strength and thus there is no influence on the composite strength. There is also one extra data point on this graph at a loading speed of 0.005 mm/min, which is a very slow test. A slight decrease in fibre strength is observed which means that near the end of the stress-strain curves the fibres will break earlier than at static loading speeds. This can be explained through a phenomenon called static fatigue. This is a well documented phenomenon for a lot of materials such as for instance glass [Fre80]. They perform less when they are subjected to slowly applied static loads, since small defects (micro-cracks), due to manufacturing or handling, are able to grow.

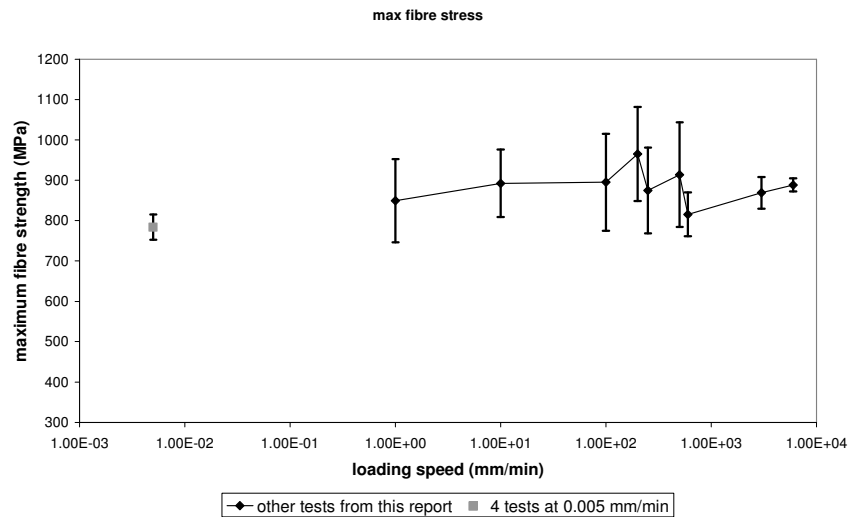


Fig. 4.3. Strength as a function for all specimens, independent of the fibre volume fraction.

One series of specimens was made in addition to the previous series of specimens in order to test them at even slightly higher strain rates. For these tests a servo hydraulic machine (MTS) was used. The strain rates which were chosen are 0.02 s^{-1} ; 0.06 s^{-1} ; 0.3 s^{-1} and 0.6 s^{-1} corresponding to loading speeds of 200 mm/min up to 6000 mm/min. The latter speed is the one where the machine is still sufficiently stable to obtain a straight displacement-time curve with a slope of 6000 mm/min. These tests indicate that the increase of the position of the intersection point seems to stagnate at a stress level of approximately 11 MPa. These tests however have to be confirmed in additional tests in the future since they are very limited now.

A final comment concerning eventually future work on this topic can be stated here: it was found in this research that the results on specimens containing 4 layers of fibres show generally more scatter (higher spreading on the results) on most parameters than on specimens containing 8 layers. This is logical since for a test piece that is thinner and thus possesses less fibre layers there are relatively more defects present in the material in an unloaded state. For test pieces with many layers, these defects are averaged more. It is therefore appropriate for further studies to test specimens with 8 or more layers of fibres.

5 CONCLUSIONS

In the presented work the aim was to identify the influence of strain rate on the tensile behaviour of glass fibre reinforced IPC composite laminates. The applied strain rates are all part of a quasi static range, with the highest values getting near low velocity impact. Several series of specimens were tested showing that the strain rate does influence the tensile stress-strain behaviour. The main damage mechanisms in the tensile behaviour of the material stay the same. However, at higher strain rates the multiple cracking mechanism is delayed to higher stress levels, which leads to a larger linear elastic stage. This can be explained by assuming that at higher strain rates the fibre-matrix interface and the cement matrix itself do not get sufficient time to develop damage.

This research will certainly have its effect on the way impact on IPC composites can be modelled. If the strain rate effect is taken into account in designing impact absorbing or impact resistant applications, the material can be used in a more optimal way. In the future it would be the aim to develop a simple model or a database describing the real stress-strain behaviour at different strain rates.

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